

ACTIVE COMPLIANCE CONTROL STRATEGIES FOR MULTIFINGERED ROBOT HAND

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*Dedicated to my beloved parents
and family*



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PERPUSTAKAAN TUNKU TUN AMINAH

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ABSTRACT

Safety issues have to be enhanced when the robot hand is grasping objects of different shapes, sizes and stiffness. The inability to control the grasping force and finger stiffness can lead to unsafe grasping environment. Although many researches have been conducted to resolve the grasping issues, particularly for the object with different shape, size and stiffness, the grasping control still requires further improvement. Hence, the primary aim of this work is to assess and improve the safety of the robot hand. One of the methods that allows a safe grasping is by employing an active compliance control via the force and impedance control. The implementation of force control considers the proportional–integral–derivative (PID) controller. Meanwhile, the implementation of impedance control employs the integral sliding-mode controller (ISMC) and adaptive controller. A series of experiments and simulations is used to demonstrate the fundamental principles of robot grasping. Objects with different shape, size and stiffness are tested using a 3-Finger Adaptive Robot Gripper. The work introduces the Modbus remote terminal unit [RTU] protocol, a low-cost force sensor and the Arduino IO Package for a real-time hardware setup. It is found that, the results of the force control via PID controller are feasible to maintain the grasped object at certain positions, depending on the desired grasping force (i.e., 1N and 8N). Meanwhile, the implementation of impedance control via ISMC and adaptive controller yields multiple stiffness levels for the robot fingers and able to reduce collision between the fingers and the object. However, it was found that the adaptive controller produces better impedance control results as compared to the ISMC, with a 33% efficiency improvement. This work lays important foundations for long-term related research, particularly in the field of active compliance control that can be beneficial to human–robot interaction (HRI).

ABSTRAK

Aspek keselamatan perlu dipertingkatkan ketika robot tangan mengendalikan objek yang mempunyai kepelbagaian bentuk, struktur dan kekerasan. Ketidakupayaan untuk mengawal daya memegang dan kekakuan jari boleh menimbulkan isu ketika robot tangan mengendalikan objek. Meskipun telah banyak kajian dijalankan bagi menyelesaikan isu memegang objek terutamanya bagi objek yang mempunyai pelbagai saiz, struktur dan kekerasan, kawalan daya memegang masih memerlukan penambahbaikan. Oleh itu, sasaran utama kajian ini adalah untuk menilai dan menambah baik aspek keselamatan robot tangan. Salah satu kaedah yang membenarkan proses genggam yang selamat adalah dengan mengaplikasikan kawalan patuh aktif menerusi kawalan daya dan kawalan impedans. Implementasi kawalan daya dilaksanakan dengan menggunakan kawalan perkadaran-kamiran-derivatif (PID). Manakala, pelaksanaan kawalan impedans adalah dengan menggunakan kawalan mod kamiran gelongsor (ISMC) dan kawalan penyesuaian. Satu siri eksperimen dan simulasi dijalankan bagi menjelaskan prinsip asas proses menggenggam oleh robot. Objek dengan pelbagai bentuk, saiz dan kekerasan diuji dengan menggunakan robot-3-jari-penyesuai-penggenggam. Kajian ini turut memperkenalkan protokol unit terminal kawalan jauh Modbus [RTU], sensor daya kos rendah dan Pakej Arduino IO bagi penyediaan perkakasan masa-sebenar. Hasil kajian mendapati kawalan perkadaran-kamiran-derivatif (PID) menunjukkan keupayaan jari-jari robot untuk mengekalkan sentuhan dengan objek pada posisi tertentu, bergantung kepada daya yang dikehendaki (1N dan 8N). Sementara itu, pelaksanaan kawalan impedans melalui kawalan mod kamiran gelongsor (ISMC) dan kawalan penyesuaian menghasilkan pelbagai tahap kekakuan pada jari robot serta mampu mengurangkan pertembungan antara jari robot dan objek. Walaubagaimanapun, kawalan penyesuaian didapati mendapat hasil yang lebih baik berbanding kawalan mod kamiran gelongsor (ISMC), dengan penambahbaikan kecekapan sebanyak 33%. Kajian ini meletakkan asas yang penting untuk penyelidikan jangka masa panjang, terutamanya dalam bidang

kawalan patuh aktif yang boleh memberi manfaat kepada interaksi manusia-robot (HRI).



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LIST OF SYMBOLS AND ABBREVIATIONS

ACT	- Anatomically-correct testbed
ADC	- Analog to digital converter
Anthrobot	- Anthropomorphic robot hand
BERUL	- Bristol elumotion robot hand
BRL	- Bristol robotics laboratory
Cyband	- Cybernetics robot hand
DART	- Dexterous anthropomorphic robotic typing
DH	- Denavit hartenberg
DOF	- Degree of freedom
FBG	- Fiber bragg grating
ISMC	- Integral sliding mode control
LMEE	- Local minimum of elastic potential energy
MRAC	- Model reference adaptive controller
PID	- Proportional integral derivative
PISM	- Proportional-integral sliding mode control
RL	- Reinforcement learning
SEAs	- Series elastic actuators
SMC	- Sliding mode control
SPTS	- Single pressure tactile sensor
ST ARM AC	- Stanford testbed of an autonomous rotorcraft for multi-agent control
VSSs	- Variable-structure systems
Z	- Impedance
k	- Stiffness
b	- Viscous damping coefficient
I_i	- Inertia
T_{gen}	- Generated torque
ω	- Actual speed
α	- Actual acceleration
τ	- Joint torque vector for modelling contact
M	- Mass matrix for modelling robot finger
V	- Resulting coriolis matrix for modelling robot finger
G	- Gravitational force vector for modelling robot finger
F_r	- Friction force vector
q	- Joint position vector
qf	- Coordinate vector describing the combined configuration of the system consisting of one or more parts and robot fingers
W	- Grasp matrix that maps the individual fingertip contact wrenches

f_{all}	-	Vector obtained by stacking the wrench at an active contact
c_i	-	An active contact
M_f	-	Mass matrix for modeling constant
C	-	Resulting coriolis matrix for modelling contact
g	-	Gravitational force vector for modelling contact
T_f	-	Control forces for modelling contact
T_f	-	Joint torque vector for modelling contact
F	-	Force
N^T	-	Null space operation
I	-	Identity matrix
U	-	Cost function
K_a	-	Actuator activation matrix
f_u	-	Unknown but bounded some known functions of the states
s	-	Sliding mode surface
c	-	Constant
x	-	Position error
M_i	-	Constant
sgn	-	Signum
\dot{x}	-	Velocity error
q_e	-	Tracking error
Θ_1	-	Angular data of joint 1
Θ_2	-	Angular data of joint 2
Θ_3	-	Angular data of joint 3
X_0	-	Reference frame
Y_0	-	Reference frame
Z_0	-	Reference frame
VG_1	-	Lumped expressions of coriolis/centrifugal force and gravity
VG_2	-	Lumped expressions of coriolis/centrifugal force and gravity
VG_3	-	Lumped expressions of coriolis/centrifugal force and gravity
T_1	-	Actual torque joint 1
T_2	-	Actual torque joint 2
T_3	-	Actual torque joint 3
T_D	-	Driving torque joint 1
T_{L21}	-	Load torque joint 1
T_{L22}	-	Driving torque joint 2
T_{L31}	-	Load torque joint 2
T_{L32}	-	Driving torque joint 3
r_1	-	Radius of the first pulley
r_{21}	-	Radius of the second pulley
k_{12}	-	Constant to take into account offset
r_{22}	-	Radius of the second pulley
r_3	-	Radius of the third pulley
k_{22}	-	Constant to take into account offset
f	-	Lumped expression for the major nonlinearities
q_d	-	Desired trajectory
$q'd$	-	Desired trajectory velocity

\ddot{q}_d	-	Desired trajectory acceleration
r	-	Filtered control error
\dot{q}_r	-	Reference trajectory velocity
\ddot{q}_r	-	Reference trajectory acceleration
λ	-	Constant
k_1	-	Constant
k_i	-	Integral Constant
\hat{f}	-	An estimate of the friction force
\hat{M}	-	An estimate of the mass
S	-	Basis functions used for friction identification
P	-	A vector of parameters
ε	-	A small remaining error
\tilde{f}	-	Actual of the friction force - estimate of the friction force
\tilde{M}	-	Actual of the mass - estimate of the mass
u_r	-	Compensate for any remaining modeling uncertainty ε
k_2	-	Constant
$\hat{\Theta}$	-	Adapting law
$\tilde{\Gamma}$	-	Adapting law
ψ	-	Adapting law
σ	-	A forgetting factor
τ_0	-	Computed torque component
τ_1	-	Discontinuous torque control
M_0	-	Nominal value
f_0	-	A discontinuous torque control
k_p	-	Proportional constant
k_d	-	Derivative constant
Γ_0	-	Gain to drive $s = 0$
K_s	-	Gain for sliding surface/damping constant
K_{is}	-	Integral gain for sliding mode control/spring constant
y_{di}	-	Demand signals
y_i	-	Output signals
N_s	-	Number of samples
u_i	-	Control signal
γ	-	Gain to suppress chattering
H	-	External force measurement signal
G_f	-	Input distribution gain
q_r	-	Virtual demand
m_v	-	Virtual mass of the spring
K_{ss}	-	Virtual damping constant
K_{ii}	-	Virtual spring constant
ω_n	-	Natural frequency
ζ	-	Damping ratio coefficient
R_d	-	Desired radial
\dot{R}_d	-	Desired radial velocity
\ddot{R}_d	-	Desired radial acceleration
R_e	-	Radial error
F_0	-	PD controller
F_1	-	Integral sliding mode controller

B	-	Projection matrix
\hat{s}	-	Sliding mode variable for the posture control
δ_{SL}	-	Gain to suppress chattering for the posture control
K_{dp}	-	Constant
K_{SL}	-	Constant
K_v	-	Constant
w_1	-	Constant
w_2	-	Constant
ϕ_1	-	Constant
ϕ_2	-	Constant
R_r	-	Virtual demand
H	-	External force
G_f	-	Positive scalar
K_s	-	Damping coefficient
K_i	-	Stiffness coefficient



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CHAPTER 1

INTRODUCTION

1.1 Research Background

Robots are commonly used in highly structured and pre-defined environments, such as factories. Tasks such as painting, deburring, polishing and welding require robots to move from initial positions to goal positions efficiently, without colliding with obstacles or other robots [1]. The unstructured robot environment (i.e., an environment in which the robot has no prior knowledge of the environment) has been a subject of interest for many researchers, particularly when the robots are sharing the same workspace as humans or other robots [2]. This scenario requires researchers to focus on safety issues during interactions between the robot and its surroundings. For example, the safety of an object being grasped by a robot hand relies on several aspects, such as the provision of reliable mechanical structures or mechanisms in the robot, the presence of adequate motion control and the feasibility of compliance control [3], [4], [5], [6].

In general, compliance control can be divided into two categories: active compliance control and passive compliance control. Active compliance control uses the force feedback method, while passive compliance control applies elements of elasticity and mechanical structure to specifically generate compliance tasks at the robot endpoint [7]. Over the last ten years, work on active and passive compliance control in robot hands has been performed extensively in the effort to imitate human hand capability. Figure 1.1 summarises the general concepts of passive and active compliance control.

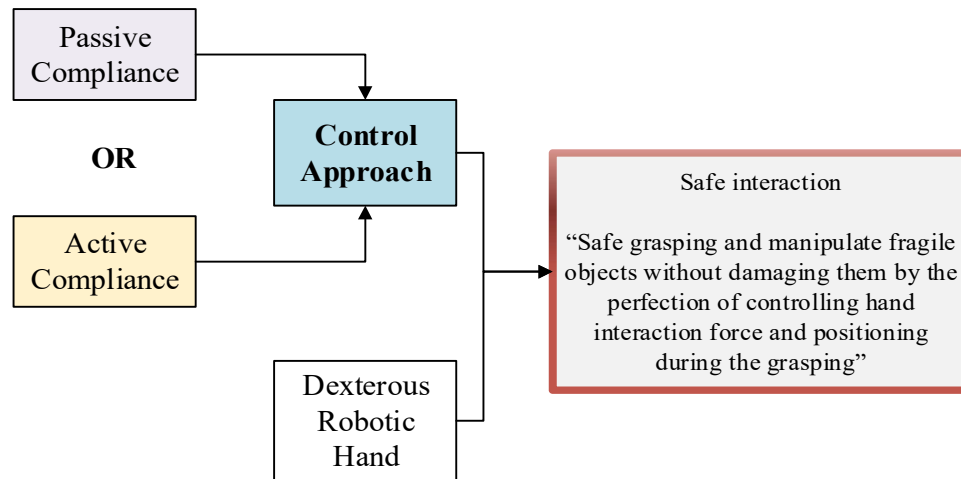


Figure 1.1: General Concept of Passive and Active Compliance Control

Past research on compliance control strategy has shown that position control has been used more commonly than force control to produce fast, accurate and repeatable robot motion. Moreover, position control works best in a well-organised and controlled work space because the controlled robots operate repeatedly in the same working area, such as in the automation manufacturing industry. However, position control is not enough when extending the application of robots outside of the controlled working environment to tasks that involve contact with objects when position data are not entirely known. The use of pure position control can result in fluctuations in contact force that ultimately lead to dangerous behaviours such as breakage or instability. Therefore, many compliance controls strategy for robot movement, and specifically for robot hands, have been introduced by researchers to replicate safe human grasping and object contact. This work focuses on compliance control strategy, particularly in relation to a robot hand.

1.2 Research Context

This research focuses on the active compliance control approach for a robot hand grasping operation. Generally, an active compliance control can be divided into two categories: force control and impedance control [8]. This is depicted in Figure 1.2.

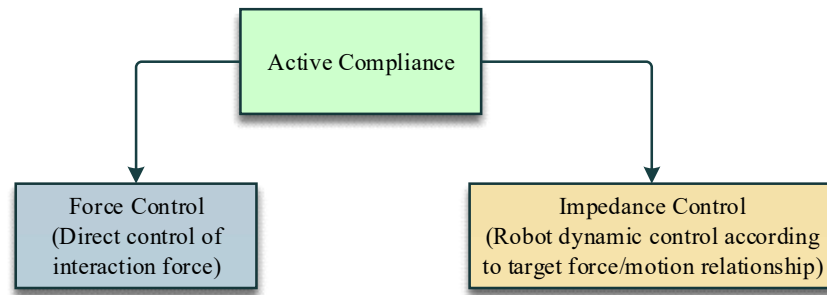


Figure 1.2: Active Compliance Control Categories

Force control is defined as a control technique in which the desired interactions between force and robot position are controlled. In force control, the desired force trajectory is commanded, and force is measured in real time to enable feedback control. Conversely, impedance control is based on position control, and it requires positioning commands and measurements to close the feedback loop. In addition, force measurements are also required to realise the target impedance characteristic. It uses the different relationships between the acting forces and manipulator position to adjust the mechanical impedance of the end-effector to the external forces.

The most common types of impedance control are stiffness (position proportional), damping (velocity proportional) and general impedance (position, velocity and acceleration proportional) [8]. The impedance causality implementation is more robust in terms of rigid contact, but the admittance control scheme is more widely applicable and has better nominal performance in free motion.

The context of this research includes both force and impedance control approaches. The proposed force control utilises proportional–integral–derivative (PID) controller, while the impedance control uses two different controllers, namely, integral sliding-mode controller (ISMC) and adaptive controller (friction compensation–based).

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